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A PRELIMINARY REPORT ON THE BEHAVIOR OF THE PACIFIC SARDINE *(SARDINOPS CAERULEA)* IN AN ELECTRICAL FIELD

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Hermann (1885) found that small fish in a direct-current (d.c.) field of a certain density oriented themselves so as to face the anode, or positive pole, and swam toward that pole. When the current was reversed, the fish turned 180° and swam toward the other electrode, the new positive pole. This was confirmed by Blasius and Schweizer (1893), Nagel (1895), Scheminzky (1924), and others.

Since this early work, the galvanotropic reaction of fish has been utilized in this country in the development of electrical fish screens (McMillan, 1929); in the sampling of fresh-water fish populations by Haskell (1939), Haskell and Zilliox (1940), Larimore *et al.* (1950), and by several Canadian workers (Canadian Fish Culturist, 1950); and in studies now being undertaken to develop methods for the elimination of undesirable fresh-water fishes. Success has been reported in the use of electrical methods in commercial fresh-water fisheries in Russia by Chernigin (Anon., 1950) and in Germany by Denzer (1949).

Attention has most recently centered on the possible use of electricity in marine fisheries in Germany by workers utilizing equipment developed

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by Kreutzer and Peglow, as reported by Houston (1949). Since details of this equipment and the application of its use have not been made generally available, the research reported on below has been undertaken to determine the behavior of the Pacific sardine in an electrical field.

Although this research has been conducted on a laboratory scale thus far, the application of the principles involved to electrical fishing methods in marine fisheries may prove of great value. Such fishing methods may make possible the utilization of so-called "wild" schools of fishes and other marine fishes now difficult to obtain by the use of nets alone.

A wooden tank, 13′ 7½″ long, 20″ wide, and 12″ deep, filled with sea water to a depth of 6 to 7 inches was used (fig. 1). Temperature of the sea water during the course of the experiments varied from 14° C. to 16° C. The water was aerated at all times.

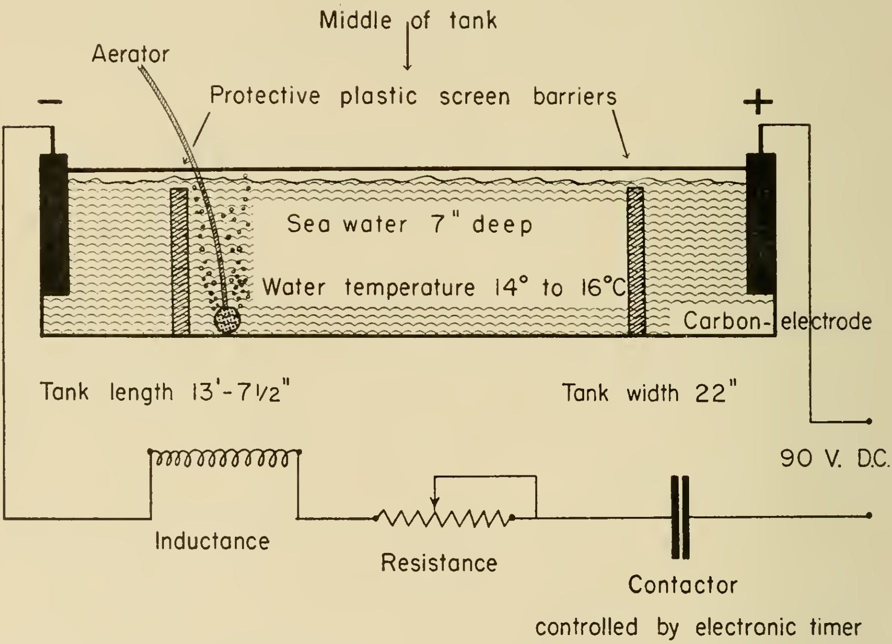

Figure 1. Diagram of experimental tank and electrical circuit.

Carbon electrodes measuring 5″ x 6″ x ¾″ were placed vertically at each end of the tank. Plastic screens were inserted 2 feet in front of each electrode to prevent direct contact with the fish. Pulsating direct current was supplied to the electrodes from a direct-current generator. The amount of current supplied to the tank was controlled by a variable resistor, and the wave form of the current impulse (fig. 2) was produced by the use of an inductance in the tank circuit. Timing of the impulses was controlled by an electronic timer which operated a small contactor to close and open the circuit. To check the wave form, an oscilloscope was included in the circuit. The circuit was arranged so that the polarity of the electrodes could be reversed.

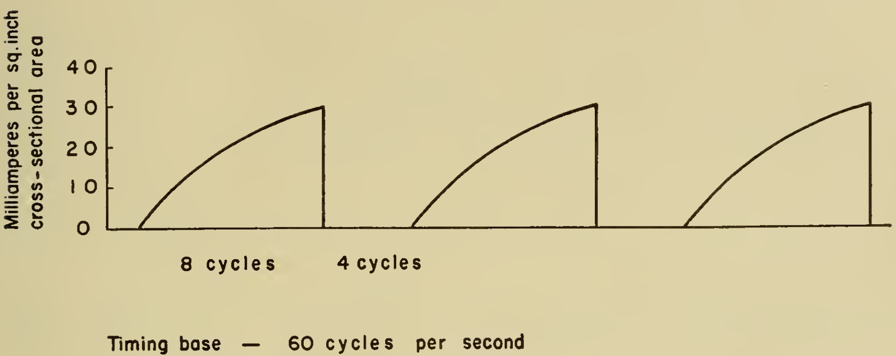

Figure 2. Diagram of effective electrical wave form.

Before each experiment the fish not previously tested were transferred from 1,000-gallon holding tanks to the experimental tank. They were permitted to remain undisturbed for a period of from 1 to 2 hours for purposes of acclimatization. The effectiveness of this acclimatization period was tested by the addition of live brine shrimp *(Artemia salina)*. Normal feeding behavior exhibited by the fish was used as an indication of their adjustment to the conditions of the experimental tank.

Following this period of acclimatization, from 2 to 4 fish were subjected to the various types of current listed below. Behavior patterns were recorded by an observer and by motion-picture photography. In all experiments the current density was within the limits of 15 to 35 milliamperes per square inch of cross-sectional area of water, unless otherwise stated.

The following types of direct current were found to elicit various reproducible responses on the part of the sardines:

1. Straight d.c. supplied by the d.c. generator (welding equipment).

2. Pulsating d.c. produced by hand switch or electronic timer with a pulsation rate of from 3 to 12 per second.

3. Pulsating d.c. with the current reduced to ½ ampere between pulsations.

4. Pulsating d.c. with the current cut to the zero point between pulsations, with the current on 2 times as long as off.

5. Pulsating d.c. with the current cut to the zero point between pulsations, with the current off 2 times as long as on.

The sardines were also tested with the types of electrical currents listed below, with variations in equipment used where necessary. None of these currents produced directional movements.

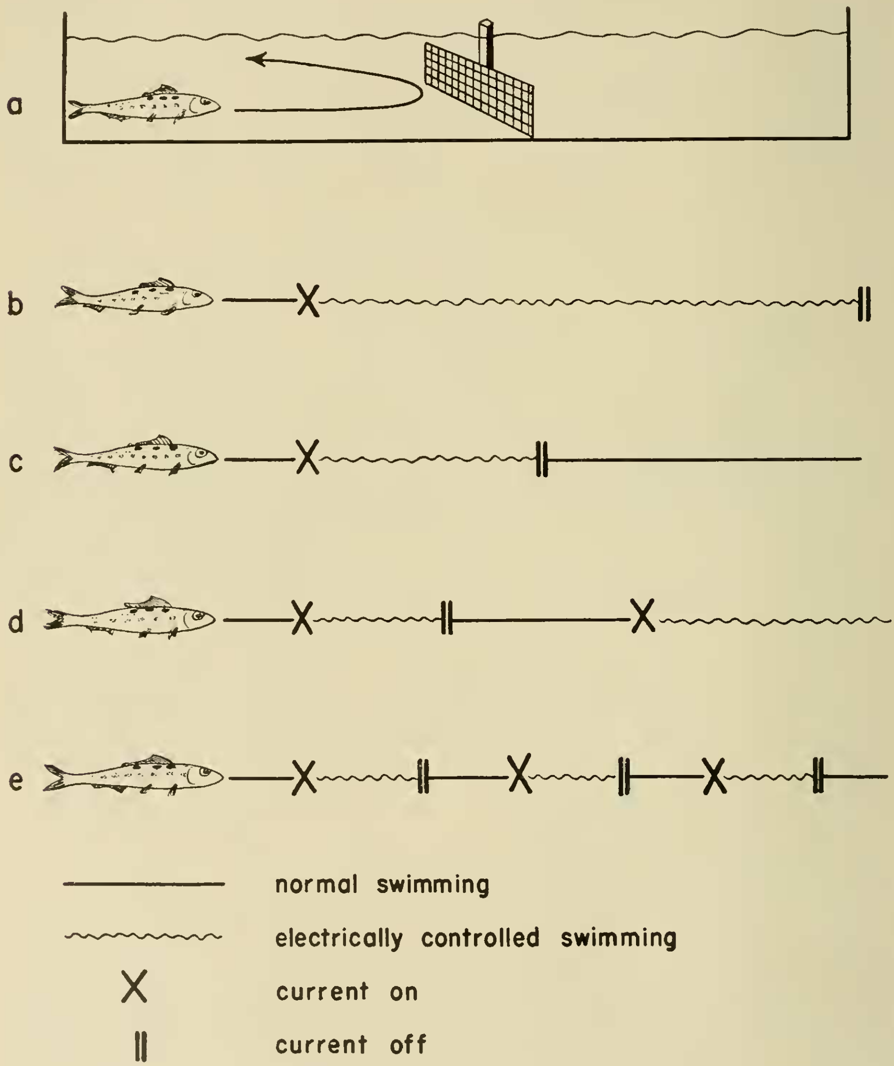

Figure 3. Diagram illustrating behavior of sardines in the absence and in the presence of an electrical field.

1. Rectified alternating current (a.c.) produced by a full-wave rectifier delivering a current with low pulsating peaks of 120 cycles per second.

2. Rectified a.c. with on-and-off pulsations from 3 to 20 cycles per second.

3. Condenser discharge produced by the use of an approximately 50 microfarad condenser with a voltage variation of from 100 to 600 volts. The frequency of discharge was varied from 4 to 8 per second.

The type of current found to be most effective in controlling sardine movements was a pulsating direct current (4, page 313) with the wave pattern shown in figure 2.

As can be seen in figure 2, the current density began at zero, increased to a maximum of 30 milliamperes per square inch of cross-sectional area of water for a duration of 8 cycles, and then returned to zero for 4 cycles. These pulses were repeated 5 times per second. Under the influence of this current, the fish immediately oriented themselves to face the positive pole and swam toward that pole. During the period of electrically controlled movement, the fish swam more slowly and laboriously than normal with no periods of relaxation. It appeared to the observer that the fish were being forced to swim.

Sardines swimming freely in the experimental tank did not show any set patterns of movement. Their swimming was continuous and they showed no preference for either end of the tank. Upon introduction of a plastic screen barrier, the fish exhibited typical fright reactions, such as an erratic increase in speed of swimming and immediate avoidance of the barrier by turning and swimming away from it (fig. 3a). Similar fright reactions resulted when the observer struck the water surface or sides of the tank with his hands, or when he moved a white object above the fish.

In the presence of an electrical field having the characteristics shown in figure 2, the behavior of the sardines changed markedly. This behavior may be grouped into four general classes as follows:

1. Fish facing the positive pole at the time the current was turned on continued to swim in a forced manner toward that pole (fig. 3b, c, d, and e). The type of swimming movements exhibited under influence of the current has been described above.

2. Fish facing the negative pole at the time the current was turned on oriented immediately to face the positive pole and swam in a forced manner toward that pole (fig. 4a and b).

3. When the charge on the poles was suddenly reversed during the forced swimming of the sardines, the fish reoriented to face the new positive pole and continued the forced swimming toward that pole (fig. 4c). This reversal of poles could be repeated many times with the same results (fig. 4d).

4. The insertion of a plastic screen between the sardines and the positive pole when the current was on resulted in no fright reactions. The fish struck the barrier and attempted to circumvent it. Those succeeding in bypassing the barrier continued their forced swimming toward the positive pole (fig. 4c). Under the influence of the current the sardines did not respond to such normally disturbing stimuli as vibrations, blows on the water surface, or the movement of white objects above them.

Topsmelt *(Atherinops affinis)* and northern anchovies *(Engraulis mordax)*, when subjected to the same current, behaved in an identical manner.

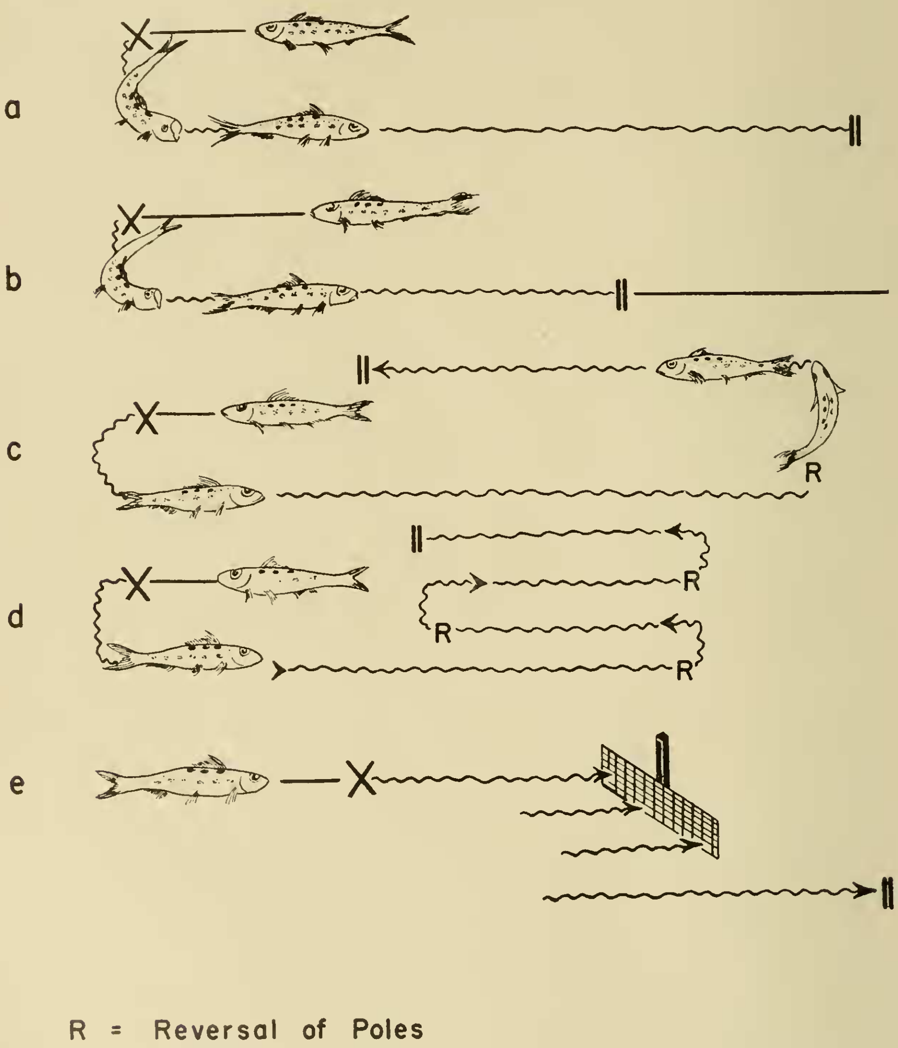

Figure 4. Diagram illustrating behavior of sardines in an electrical field.

It was found, however, that the current density required to produce these effects appeared to vary inversely with the size of the fish. For example, sardines 200 to 230 mm. in standard length oriented and swam toward the positive pole in a current with a density of 25 to 30 milliamperes per square inch. Topsmelt 110 to 120 mm. in standard length required a current density of from 35 to 40 milliamperes for the same response. This is in agreement with the findings of others (Houston, 1949).

Prior to the use of protective screens in front of the electrodes, some sardines were killed by coming into direct contact with the positive pole. After the addition of screens, no fatalities occurred, even after the fish had been intermittently subjected to the current for as long as 2 hours.

The period of captivity seemed to have no bearing on the reactions of sardines to electrical stimulation. Sardines recently received from San Diego responded in the same manner as sardines held under aquarium conditions for several months.

The current wave form (fig. 2) found to be most effective in producing directional swimming was varied in three ways; namely, by changes in (1) current density, (2) frequency of pulsations, and (3) relative duration of current-on periods to current-off periods. In order to determine the most effective combination of these variables, a series of tests were conducted utilizing the equipment and triangular wave form described above.

The conditions of the experiments were as follows:

Water depth	6 inches
Water temperature	14° C. to 18° C.
Number of fish each observational period	4
Standard length of fish	200 mm. to 230 mm.
Duration of observational period	15 seconds
Position of fish when current is turned on	Near negative pole
Type of test	Current on, then poles reversed three times

The current densities that were explored were 10, 15, 20, 25, and 30 milliamperes per square inch. Densities higher than 30 were found to be injurious and those lower than 10 were without effect. The frequencies of pulsation used were 2, 4, and 6 per second and the ratios of current-on to current-off periods were 1:3, 1:2, 1:1, 2:1, and 3:1.

For purposes of evaluating and recording the sardines' responses to the different combinations of these variables, the following definitions were used:

Perfect. When all four fish responded readily to each reversal of the poles and displayed a directional reaction toward the positive pole.

Good. When three of the four fish displayed the reaction given above or when all four fish failed to respond to one of the three reversals of poles.

Fair. When two of the fish readily responded to all pole reversals, or when all fish responded to at least two reversals.

None. When one or none of the fish displayed directional reactions.

In addition to the above definitions for recording behavior, records were made of the fishes' response to the current relative to fright reactions to stimuli and to apparent control of their own swimming movements. For these records, the following symbols were used:

(—). Swimming movements apparently under control of the fish, no directional response, and all reactions to fright stimuli retained.

(½+). The avoidance reaction to the barrier was retained, but the fish did not respond to vibrations of the tank with fright reactions.

(+). Directional responses apparently controlled by electrical current density only. Normal fright reactions to the barrier or to other stimuli completely lost.

(++). In addition to the reactions above under (+), the fish remained in contact with the protective screen next the positive pole as long as the current was on. This was, of course, the most pronounced reaction to the current short of stunning and death.

The method of varying the wave pattern consisted of maintaining each of two variables at the most effective level as determined from the earlier tests and changing the third variable according to the points listed above. For example, the pulsation rate was held at 4 times per second, and the ratio of current-on to current-off periods held at 2:1, while the current density was changed from 10 to 30 milliamperes per square inch by 5 milliampere increments. The density was then held at 30 milliamperes per square inch while the other variables were changed.

The most effective current densities were 25 and 30 milliamperes per square inch (table 1). Out of 180 tests for each of these densities, "satisfactory" results were obtained in 86.7 and 88.9 per cent respectively. These percentages were higher than those obtained for the lower densities. Accordingly, control of fish movement was "satisfactory" in 66.7 and 76.7 per cent of the tests at the two higher densities.

Four and six pulsations per second gave "satisfactory" results in producing directional reactions in 78.0 and 79.7 per cent respectively of 300 tests at each rate (table 2). Control of movement was "satisfactory" in 46.0 and 48.7 per cent of the tests at these rates.

The ratios of current-on to current-off periods found to give "satisfactory" results in directional reaction were 2:1 and 3:1, with 87.8 and 88.9 per cent respectively out of 180 tests at each ratio (table 3). Control of

TABLE 1

SARDINE REACTIONS TO VARIATIONS IN CURRENT DENSITY

Directional Reaction

Density in milli-amperes	Number of observations							Percentage of observations						
	None	Unsatisfactory Fair	Both	Good	Satisfactory Perfect	Both	Total	None	Unsatisfactory Fair	Both	Good	Satisfactory Perfect	Both	Total
10	41	61	102	69	9	78	180	22.8	33.9	56.7	38.3	5.0	43.3	100
15	8	62	70	79	31	110	180	4.4	34.5	38.9	43.9	17.2	61.1	100
20	6	30	36	82	62	144	180	3.3	16.7	20.0	45.6	34.4	80.0	100
25	2	22	24	76	80	156	180	1.1	12.2	13.3	42.2	44.5	86.7	100
30	0	20	20	65	95	160	180	0	11.1	11.1	36.1	52.8	88.9	100

Control of Movement

Density in milli-amperes	Number of observations							Percentage of observations						
	Minus	Unsatisfactory ½ plus	Both	Plus	Satisfactory Pl. plus	Both	Total	Minus	Unsatisfactory ½ plus	Both	Plus	Satisfactory Pl. plus	Both	Total
10	112	66	178	2	0	2	180	62.2	36.7	98.9	1.1	0	1.1	100
15	86	62	148	32	0	32	180	47.8	34.4	82.2	17.8	0	17.8	100
20	38	50	88	76	16	92	180	21.1	27.8	48.9	42.2	8.9	51.1	100
25	22	38	60	52	68	120	180	12.2	21.1	33.3	28.9	37.8	66.7	100
30	10	32	42	48	90	138	180	5.5	17.8	23.3	26.7	50.0	76.7	100

TABLE 2

SARDINE REACTIONS TO VARIATIONS IN CURRENT PULSATION RATE

Directional Reaction

Pulsations per second	Number of observations							Percentage of observations						
		Unsatisfactory			Satisfactory				Unsatisfactory			Satisfactory		
	None	Fair	Both	Good	Perfect	Both	Total	None	Fair	Both	Good	Perfect	Both	Total
2	24	101	125	107	68	175	300	8.0	33.7	41.7	35.7	22.6	58.3	100
4	16	50	66	132	102	234	300	5.3	16.7	22.0	44.0	34.0	78.0	100
6	17	44	61	132	107	239	300	5.7	14.6	20.3	44.0	35.7	79.7	100

Control of Movement

Pulsations per second	Number of observations							Percentage of observations						
		Unsatisfactory			Satisfactory				Unsatisfactory			Satisfactory		
	Minus	½ plus	Both	Plus	Pl. plus	Both	Total	Minus	½ plus	Both	Plus	Pl. plus	Both	Total
2	123	77	200	50	50	100	300	41.0	25.7	66.7	16.7	16.6	33.3	100
4	82	80	162	78	60	138	300	27.3	26.7	54.0	26.0	20.0	46.0	100
6	63	91	154	82	64	146	300	21.0	30.3	51.3	27.3	21.4	48.7	100

TABLE 3

SARDINE REACTIONS TO VARIATIONS IN RATIO OF CURRENT-ON TO CURRENT-OFF

Directional Reaction

Ratio of current-on to current-off	Number of observations							Percentage of observations						
	None	Unsatisfactory Fair	Both	Good	Satisfactory Perfect	Both	Total	None	Unsatisfactory Fair	Both	Good	Satisfactory Perfect	Both	Total
1:3	19	85	104	69	7	78	180	10.6	47.2	57.8	38.3	3.9	42.2	100
1:2	17	38	55	102	23	125	180	9.4	21.1	30.5	56.7	12.8	69.5	100
1:1	14	37	51	80	49	129	180	7.8	20.5	28.3	44.5	27.2	71.7	100
2:1	7	15	22	78	80	158	180	3.9	8.3	12.2	43.3	44.5	87.8	100
3:1	0	20	20	42	118	160	180	0	11.1	11.1	23.3	65.6	88.9	100

Control of Movement

Ratio of current-on to current-off	Number of observations							Percentage of observations						
	Minus	Unsatisfactory ½ plus	Both	Plus	Satisfactory Pl. plus	Both	Total	Minus	Unsatisfactory ½ plus	Both	Plus	Satisfactory Pl. plus	Both	Total
1:3	110	60	170	8	2	10	180	61.1	33.3	94.4	4.5	1.1	5.6	100
1:2	65	63	128	40	12	52	180	36.1	35.0	71.1	22.2	6.7	28.9	100
1:1	41	51	92	60	28	88	180	22.8	28.3	51.1	33.3	15.6	48.9	100
2:1	30	42	72	56	52	108	180	16.7	23.3	40.0	31.0	29.0	60.0	100
3:1	22	32	54	46	80	126	180	12.2	17.7	29.9	25.6	44.5	70.1	100

movement at these two ratios was "satisfactory" in 60.0 and 70.1 per cent of the tests.

These data tend to indicate that the most effective type of current producing directional swimming and electrical control of movements of the Pacific sardine is within the range of that diagrammed in figure 2. They also show that the rate of current pulsation as far as control of movement is concerned is of less importance than the other two variables.

The application of these tests to other species of marine fishes strongly indicates that detailed analysis of the current pattern will be necessary for each kind and size of fish before the method can be applied effectively in the capture of these fishes in the open ocean.

Whether the current found in the above experiments to regulate Pacific sardine movements in the laboratory will be as effective in the sardine fishery awaits development of equipment and methods of research for use on the fishing grounds.

Summary

1. Pacific sardines *(Sardinops caerulea)* were found to respond to a pulsating direct electric current by orienting to face the anode and swimming toward that pole in a forced manner. Of the many types of current tried, the type of current wave form found to be most effective in causing this behavior was one in which the density began at zero, increased to a maximum of 30 milliamperes per square inch of cross-sectional area of water for a duration of 8 cycles, and then returned to zero for 4 cycles. Under the influence of this current the fish did not respond to stimuli normally causing fright reactions.

2. The current density required to produce directional swimming appeared to vary inversely with the size of the fish tested.

3. The fish were not killed by the above current as long as they were prevented from direct contact with the electrodes.

4. The period of captivity seemed to have no bearing on the response of the sardine to the electrical field.

5. Analysis of the relative effects of the three variables of this current, viz., density, pulsation frequency, and ratio of current-on to current-off period, tends to confirm the earlier findings that the most effective type of current producing directional swimming and electrical control of movements of the Pacific sardine is within the range of that stated above.

6. It is suggested that before the application of electrical fishing methods to marine fisheries can be made, detailed research to determine the current wave form most effective for each species and size of fish will be necessary.

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